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ORIGINAL PAPER

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DETERMINATION OF THE D_{50} PARTICLE DIAMETER IN NON-COHESIVE SOILS BASED ON DILATOMETER TESTS

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ABSTRACT

The increasing demands placed on geotechnics require the development of interpretation methods to obtain as many geotechnical parameters as possible from a single test profile. Extensive databases of documented test points were used to construct and develop a direct correlation between the measured pressures p_0 and p_1 from the dilatometer tests (DMT) and the laboratory results of grain size distribution tests of cohesionless soils from the analysed boreholes, as well as the pore water pressure (u_0). Furthermore, the analysis considered pore water pressure (u_0). The primary achievement of this paper is the development of an original correlation that enables the direct estimation of the equivalent diameter (D_{50}) of cohesionless soils based on DMT results. Furthermore, the D_{50} values calculated from the proposed relationship were validated using laboratory test results from soils from other sites not included in the analysis during the development of the proposed empirical relationship.

Keywords: in situ test, mineral soil, sand grain size

INTRODUCTION

When designing an engineering structure, many factors should be considered, including safety considerations, without which it is impossible to carry out even the most ambitious plan. The engineer's task is to gather various types of data to verify whether the soil is suitable for the designed building, allowing for the construction of solid foundations. Soil type and geotechnical parameters needed for designing are obtained from soil tests (Schneider et al., 1997; Orr, 2000; Młynarek, 2007; Bond & Harris, 2008; Wierzbicki, 2010; Młynarek, Stefaniak & Wierzbicki, 2012; Zabielska-Adamska, 2019; Tarnawski Ed., 2020; Zabielska-Adamska, 2020; Rasti, Adarmanabadi, Pineda & Reinikainen, 2021). Soil investigations are thus indispensable here. They can be subdivided into field and laboratory tests. Laboratory tests have several advantages, including accuracy, a well-defined stress state, and the ability to control drainage conditions (Gryczmański, 1995; Pisarczyk, 2014; Cichy, Lechowicz & Garbulewski, 2017). In situ tests, the subject of this article, are used to test soil parameters directly in the field. Based on them, it is possible to determine the geotechnical parameters of soils in their natural state. The most common in situ soundings include the cone penetration test (CPT) and the Marchetti dilatometer test (DMT) (Schmertmann, 1978; Marchetti, 1980; Lunne, Robertson & Powell, 1997; Mayne, Martin & Schneider, 1999; Fellenius & Eslami, 2000; Młynarek, Gogolik & Marchetti, 2006; Młynarek, 2007; Bałachowski & Kurek, 2008; Godlewski & Wszędyrówny-Nast, 2016; Hakam, Febriansyah & Adji, 2020;

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Nepelski, 2020; Tankiewicz & Bagińska, 2021; Robertson & Cabal, 2022; Mayne, Greig & Cargille, 2024; Mayne, Cargille & Greig, 2025). They are also often used to supplement borehole data.

Despite significant differences in test methodology, CPT and DMT soundings are considered equivalent. For example, in Poland, research with the application of CPT and DMT probes is carried out in the following centres: Department of Engineering Geology and Geotechnics at University of Life Sciences in Poznań (Młynarek et al., 2006), Department of Geotechnics, Geology and Marine Civil Engineering at Gdańsk University of Technology (Bałachowski, 2006), Institute of Hydrogeology and Applied Geology at University of Warsaw (Kaczyński, 2017), Department of Geotechnics and Foundation at the Building Research Institute in Warsaw (Wysokiński, 2007), Department of Geotechnical Engineering at Warsaw University of Life Sciences – SGGW (Rabarijoely, 2000; Lechowicz & Rabarijoely, 2005), Institute of Geology, Faculty of Geographical and Geological Sciences at Adam Mickiewicz University in Poznań (Wierzbicki, 2010), Faculty of Civil Engineering at Cracow University of Technology (Truty & Podleś, 2018), Faculty of Civil and Environmental Engineering at University of Zielona Góra (Szajna, 2015; Szajna & Gontaszewska, 2015) and Faculty of Civil Engineering and Architecture at Lublin University of Technology (Nepelski, 2020).

The article does not describe the DMT and CPT methodologies, as this information can be found in the journal archives (Bajda, Skutnik, Lech & Rabarijoely, 2018; Rabarijoely, 2018; Rabarijoely, 2019a; Rabarijoely, 2019b). We focus here on the analysis of the accuracy of the subsoil layer identification methods and their comparison with samples taken for laboratory tests. The research was conducted on the Stegny site and the campus grounds of Warsaw University of Life Sciences – SGGW (hereinafter referred to as "the WULS-SGGW campus"). This publication aims to develop a relationship for determining the grain size (D_{50}) for sand using DMT results from both sites.

LITERATURE REVIEW

Cone penetration and the Marchetti dilatometer testing methods in geotechnical engineering

CPT and DMT tests are commonly used to identify geotechnical conditions in all engineering structures. At the same time, the cone penetration test with pore pressure measurements (SCPTu) and the seismic dilatometer test (SDMT) are also used for buildings classified in the third geotechnical category. Due to earlier practical introductions and more extensive interpretation rules, CPT and later CPTu tests were initially considered more reliable for assessing geotechnical conditions for the proposed building. Despite significant differences in test methodology, CPT and DMT tests complement each other.

When presenting Marchetti's dilatometer, an innovative research device, the soil subdivision was based on the material index (Marchetti, 1980; Cruze, 2009; Cruz, 2010; Table 1).

Table 1. Soil classification based on the material index

Soil type		Material index (I_D) [-]
Peat or sensitive clays	peat / sensitive clays	< 0.10
	clay	0.10–0.35
	silty clay	0.35–0.60
	clayey silt	0.60–0.90
	silt	0.90–1.20
	sandy silt	1.20–1.80
Non-cohesive soils	silty sand	1.80–3.30
	sand	> 3.30

Source: Marchetti (1980).

MATERIAL AND METHODS

The Stegny site and the WULS-SGGW campus site are located on a post-glacial plateau. It is a flat area located in the Mazovian basin, developed during the Neogene (Fig. 1). According to archival data, the basin bottom is composed of marls, siliceous limestones, and gaize. The thickness of Paleogene and Neogene deposits exceeds 200 m. The upper part of the Neogene is represented by Pliocene sediments, which consist mainly of motley clays with lenses and layers of sand and silt with a thickness of about 105 m. The erosive activity of waters in the periglacial and later periods, coupled with glaciotectonic deformation, resulted in a differentiated surface of Pliocene clays. Quaternary sediments with a thickness of 26–49 m occur above the clay layers. These deposits were formed through the accumulation of glacial, fluvioglacial, and fluvial sediments. At the base of the Quaternary, ice-dammed clay-silt deposits with silt interbeds occur (Morawski, 1984; Barański et al., 2004).

Fig. 1. Map of Warsaw (scale 1 : 20 000) with the location of the study sites

Source: own work.

Material

This paper presents the test results for mineral subsoils obtained from the Stegny site and the WULS-SGGW campus in Warsaw, where the Department of Geotechnical Engineering carried out a laboratory and field-testing program (Lechowicz & Rabarijoely, 1996; Truty & Podleś, 2018). The grain-size distribution curve obtained from laboratory tests for mineral soils from the described sites is presented in Figure 2. The index properties of mineral soils in the Stegny site and the WULS-SGGW campus test site are presented in Table 2. Figure 3 presents the diagram chart proposed by Marchetti and Crapps for the analysed sites (Marchetti & Crapps, 1981).

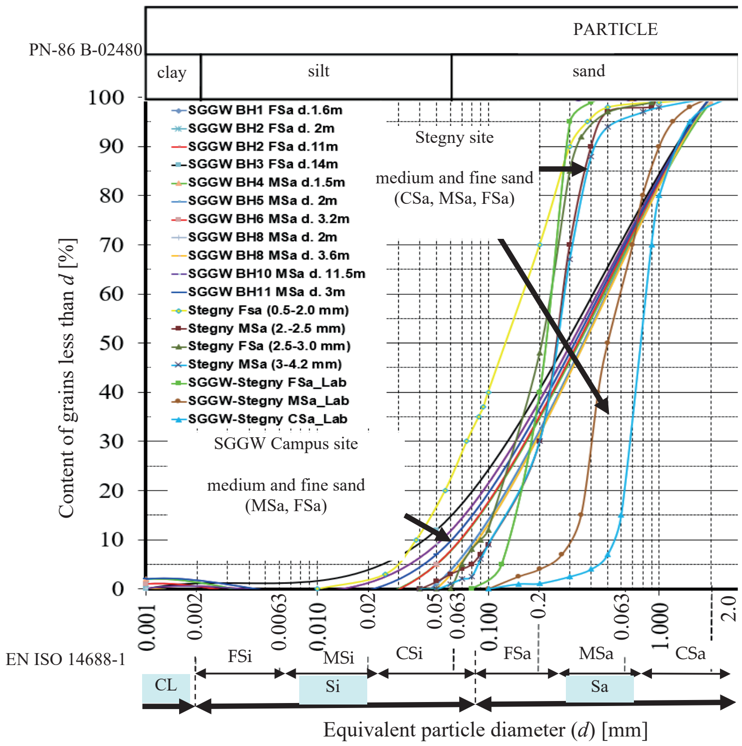

Fig. 2. Grain-size distribution curve obtained from laboratory tests for the mineral soils from the described sites

Source: own work.

Table 2. Index properties of mineral subsoils from the Stegny site and the WULS-SGGW campus test site

Site	Type of soil	Organic content (I_{om}) [%]	Calcium carbonate content [%]	Water content (w_n) [%]	Liquid limit (w_L) [%]	Density	
						Unit weight of soil (ρ) [t·m^{-3}]	Specific weight of soil ($ρ_s$) [t·m^{-3}]
Stegny	fine and medium sand (FSa, MSa)	0	< 1	5.4	–	1.7	2.68–2.66
WULS-SGGW campus	fine and medium sand (FSa, MSa)	0	1–3	6.7	–	1.85	2.68–2.66

Source: own work.

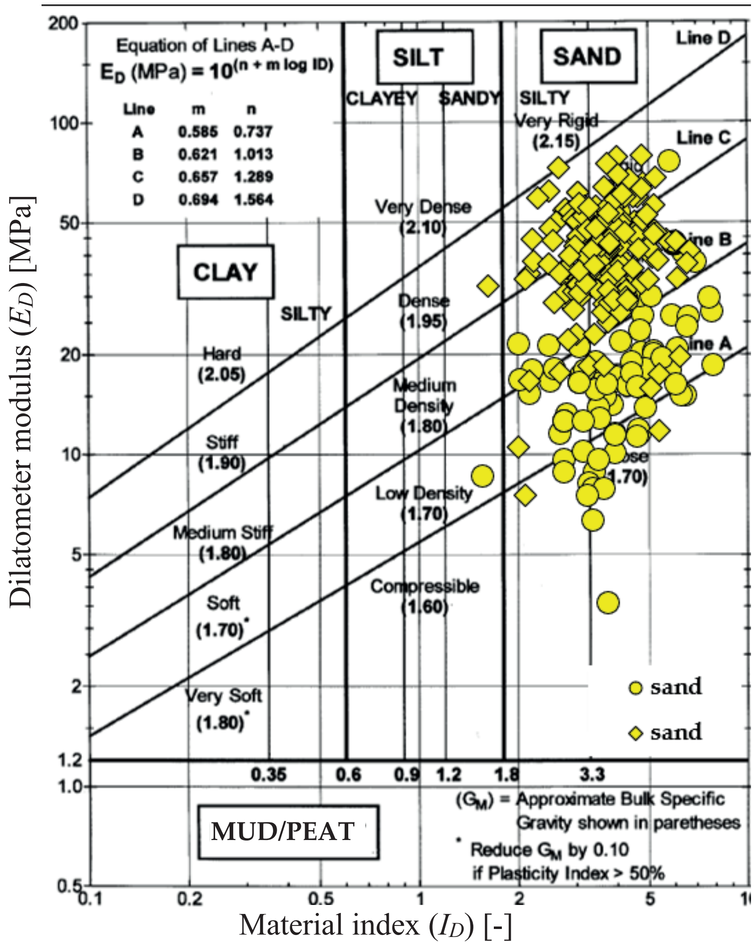

Fig. 3. Chart for estimating the unit weight (normalised to γ_w) of sands from the Stegny site and the WULS-SGGW campus test site

Source: own work based on Marchetti and Crapps (1981).

TEST RESULTS

At the Stegny site and the WULS-SGGW campus site, DMT tests were performed by the Department of Geotechnical Engineering at Warsaw University of Life Sciences – SGGW. The WULS-SGGW campus test site was in the subsoil underneath one of the buildings. The DMT soundings on the WULS-SGGW campus were performed for the future Building 34 and Building 37 (Fig. 4). The measured parameters were the pressures (p_0 and p_1), which, after conditioning, were registered by the device as pressures A and B, respectively (Fig. 4). Based on these measurements, the dilatometer indexes (3), (4), (5) were calculated and presented in Figure 5. The profiles of the material index (I_D), the horizontal stress index (K_D), and the dilatometer modulus (E_D) from the DMT for selected layers for non-cohesive soils of these two sites are shown in Figure 5. The groundwater levels are located at: (a) Stegny site – depth 3.2 m; OCR = 2.5–3.5; (b) WULS-SGGW campus site – depth 10.0 m; OCR = 3–7.

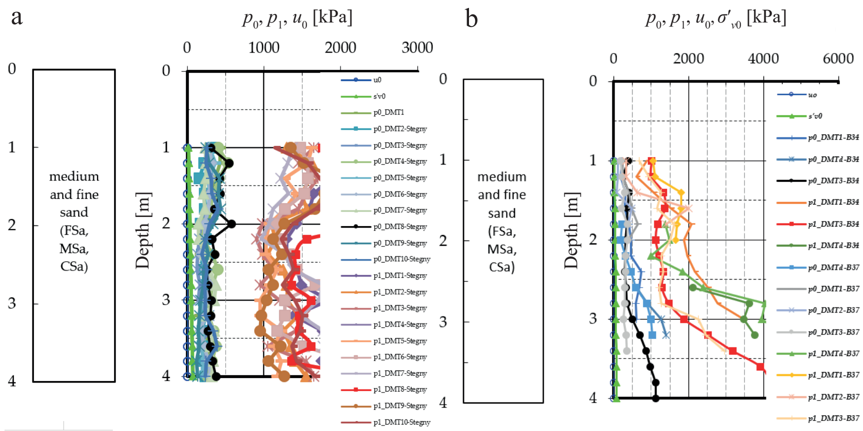

Fig. 4. Profiles of p_0 and p_1 from dilatometer tests (DMT tests, hydrostatic pressure u_0 and vertical effective stress σ'_{v0} for the Stegny site (a) and the WULS-SGGW campus site (b)

Source: Lechowicz, Rabarijoely and Szczypiński (2004), Lechowicz, Fukue, Rabarijoely and Sulewska (2018).

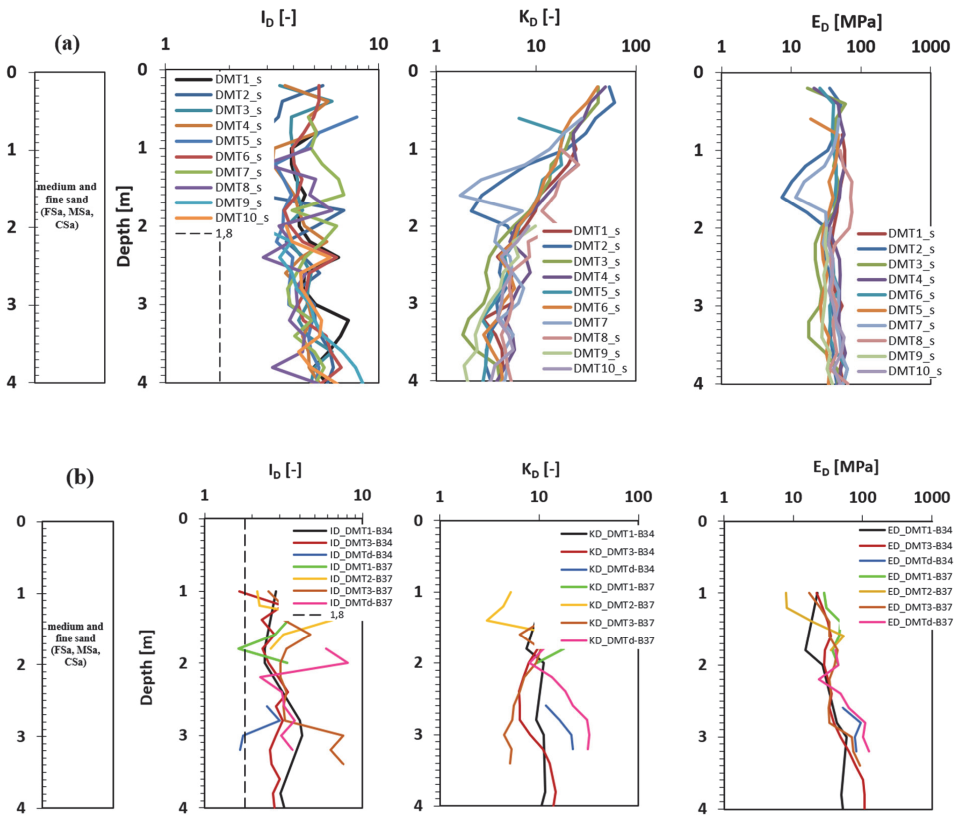

Fig. 5. Profiles of I_D, K_D, and E_D from DMT tests for the Stegny site (a) and the WULS-SGGW campus site (b) (B-34 – Building 34, B-37 – Building 37)

Source: Lechowicz et al. (2004), Lechowicz et al. (2018).

Estimation theory

A literature review reveals that the physical process in CPTu is governed by the law that describes the cone's displacement within the soil medium. It is equivalent to displacing a material point in a medium exhibiting friction (Banach, 1950; Młynarek & Sanglerat, 1983; Młynarek, 2007).

A similar mechanism also occurs in the subsoil during DMT tests. The form of the function describing DMT testing in 2008 was revealed by the research team of Professor Młynarek (Młynarek et al., 2008). Since dilatometer testing is strength and stationary testing, in which deformations of subsoil are connected with the rate pressures applied at the dilatometer tip, the equation describing this process may be written as: $F_2(P_d, V_d, \Theta_1, \Theta_2) = 0$ [where P_d – measured process parameter, e.g. pressure p_0, p_1 or $(p_0 - p_1)$, V_d – the rate at which pressure is applied onto the membrane of the dilatometer vane]. Parameter Θ_1 is recorded by the key $\Theta_1 = f(X_1, \ldots, X_9)$ [where: X_1 – effective unit weight of soil, X_2 – moisture content, X_3 – percent of organic matter, X_4 – degree of decay, X_5 – content of calcium carbonate ($CaCO_3$), X_6 – percent of clay, silt or sand fraction, X_7 – modulus of deformation of organic matter, X_8 – parameter describing shear strength, cohesion, angle of internal friction, X_9 – structure of organic soil]. Parameter Θ_2 contains the functions: $\Theta_1 = f(X_1^d, X_2^d, X_3^d)$ [where: X_1^d – variable describing the membrane geometry, e.g. diameter, X_2^d – membrane stiffness, X_3^d – membrane roughness] (Młynarek et al., 2008).

For determining parameter D_{50} based on DMT tests, parameters p_0 and p_1, as well as u_0 and σ'_{v0} were taken into account in the statistical analysis. These quantities can be treated as random variables. 17 DMT tests (including 10 DMT tests from the Stegny site and 7 DMT tests from the WULS-SGGW campus site) from the sand layer were used, with a count of 12–17 measurements (depth profiles), with 264 data points. The distribution of the tested random variables was checked. In the case of most studies, i.e. random samples in a statistical sense, there was no reason to reject the hypothesis of normality (Shapiro–Wilk tests suitable for small samples were applied; they are available, e.g. in the Statgraphics statistical software package). No other distribution was found to which the tested quantities complied (Bleistein & Handelsman, 1986).

Estimation of soil grain size (D_{50})

The aim of developing new formulas for calculating the grain size (D_{50}) of sands is to derive relations closely related to the dilatometer test, namely, the dilatometer indexes. The three main indexes obtained from a dilatometer test are: the material index (I_D), the horizontal stress index (K_D), and the dilatometer modulus (E_D). Apart from the parameters of the DMT dilatometer tests, the results of sieve tests were also used to determine the particle size distribution of sands. Several stages were employed to determine the authors' dependencies in calculating the grain size (D_{50}) of sands, which varied according to the given parameters due to different data for specific sites. The Solver module was used to determine the grain size (D_{50}) of sands based on the dependence of DMT results, which consisted of performing all the calculations carried out in this study. This function is often used for linear programming, including modelling and optimising any decision problems. This linear programming should be based on creating a reality model in which the objective function is a key element, the value of which is subordinate to a specific profitability criterion (max/min). The solution of the function is assisted by using variable coefficients (the a and b factors were assumed for the grain size D_{50} of sands determined in this paper), due to which maximum or minimum values are achieved.

Observation of the obtained results shows that there is a strong relationship between parameter D_{50} and dilatometer pressures, i.e. p_0 and p_1, as well as u_o and σ'_{v0}: $D_{50} = f(p_0, p_1, u_0, \sigma'_{v0})$. A formula was proposed for non-cohesive soils at the studied sites based on this criterion, and the lowest value of the mean square relative deviation was calculated. The formula that was used for the calculations is our original proposal. The summarised test results, i.e. I_D, K_D, and E_D values from DMT and u_0 tests, allowed us to determine the formula for the grain size (D_{50}) of sands in the following form:

$$D_{50} = f\left(a, b, p_0, p_1, u_0, \sigma'_{v0}\right), \tag{1}$$

where:
a, b – factors.

The formula was made dependent on the variables p_0, p_1, u_0, and σ'_{v0}, which belong to variable cells in the Solver function. An additional column has been added to determine the percentage deviation between the calculated D_{50} result for a given depth and the value obtained from laboratory tests. The calculations were focused on obtaining the lowest possible mean square relative deviation (*MSRD*). The values for the statistical compilation were calculated from the following formulas:
– maximal relative deviation:

$$MRD \max_{i=1,2,\ldots,m} = \left|\frac{y_i - \bar{y}_i}{y_i}\right| \cdot 100\%, \tag{2}$$

– mean square relative deviation:

$$MSRD = \left[\sqrt{\frac{1}{m}\sum_{i=1}^{m}\left(\frac{y_i - \bar{y}_i}{y_i}\right)^2}\right] \cdot 100\%. \tag{3}$$

The function was programmed to achieve the lowest possible target cell value. The results of the calculations are presented further in the text. For non-cohesive soils located in the study area, i.e. in the Stegny site and the WULS-SGGW campus site, and the data obtained from the dilatometer test, a formula was proposed, and the grain size (D_{50}) of sands was calculated.

From a physical standpoint, it is possible to determine the D_{50} value based on DMT tests, which makes it dependent on the I_D. The final form of the formula for determining the D_{50} value based on the DMT tests can be presented as follows. Using the Solver module, the values of the factors a and b for which there is the lowest value of the mean square relative deviation for the material index were determined. For the proposed formula for D_{50}, the following statistical values were obtained (summarised in Figure 6). The obtained pattern is as follows:

$$D_{50\,DMT \approx SDMT} = a \cdot e^{-\frac{b}{I_D}} \text{ [mm]}, \tag{4}$$

where:
a = 0.80,
b = 2.00,
I_D – material index [-],
e – Euler’s or Neper’s number (e = 2.72) [-].

The values obtained from the laboratory test are related to the values calculated based on Formula 4. The deviation values obtained during the calculations were acceptable, with the following results: MSRD of 13.5% and MRD of 26.0%. The correlation between the values calculated (from Formula 4) and measured is presented in Figure 6.

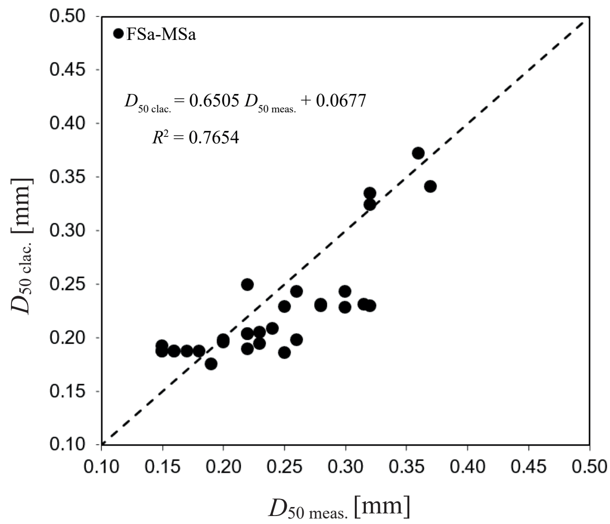

Fig. 6. Summary of the values of the soil grain size (D_{50}) obtained from laboratory tests and calculated using Formula 4 based on DMT results from the analysed Stegny site and the WULS-SGGW campus site

Source: own work.

The values calculated using the new formula align well with those obtained from laboratory tests. They behave predictably and fit into an overall trend line, while the laboratory test values have higher amplitudes. The relationship between the results obtained from laboratory tests and those determined based on Formula 4 was previously presented.

Knowledge about the mechanical strength related to D_{50} values can be used for model tests of the load-bearing capacity of surfaces made of soil mixtures, and may indirectly contribute to minimising the scope and shortening the time of laboratory and field tests. Additionally, the D_{50} value in the subsoil affects the value of the filtration coefficient, not only under the planned building.

CONCLUSIONS

Marchetti's dilatometer tests enable the measurement of soil parameters with almost continuous accuracy. They require specialised equipment and offer fast and easy testing under in situ conditions, and therefore, are very useful in obtaining soil data. The results are generally reproducible, enabling the calculation of important soil parameters used in construction and environmental engineering. To increase the reliability of the results, laboratory analysis of the soil samples should be applied. The obtained values of D_{50} for soils using the proposed new formula are comparable to those obtained directly after probing with another device or through calculation methods. The proposed formula is both convenient and user-friendly, making it very helpful for both students and designers. Despite the large dataset used in the statistical analysis, the proposed relationship should be used with caution in specific ground conditions, e.g. highly overconsolidated or cemented soils.

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Authors' contributions

Conceptualisation: S.R., M.L. and M.B.; methodology: S.R., M.B. and K.M.L.; validation: S.R. and M.B.; formal analysis: S.R., M.L. and M.B.; investigation: S.R., M.L. and M.B.; data curation: S.R., M.B. and K.M.L.; writing – original draft preparation: S.R. and M.L.; writing – review and editing: S.R. and M.L.; visualisation: S.R.; supervision: M.L. and K.M.L.

All authors have read and agreed to the published version of the manuscript.

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WYZNACZANIE ŚREDNICY ZASTĘPCZEJ CZĄSTEK PIASKU (D_{50}) NA PODSTAWIE BADAŃ DYLATOMETRYCZNYCH

STRESZCZENIE

Rosnące wymagania stawiane geotechnice wymuszają rozwój metod interpretacji umożliwiających uzyskanie jak największej liczby parametrów geotechnicznych z jednego profilu badawczego. Obszerne bazy danych z udokumentowanych punktów badawczych wykorzystano do skonstruowania i opracowania bezpośredniej współzależności między zmierzonymi dylatometrem Marchettiego (DMT) ciśnieniami (p_0, p_1) a wynikami badań laboratoryjnych uziarnienia gruntów niespoistych z próbek uzyskanych z otworów wiertniczych. Ponadto w analizie uwzględniono ciśnienie wody w porach (u_0). Głównym osiągnięciem artykułu jest uzyskanie oryginalnej współzależności, która umożliwia oszacowanie wartości średnicy zastępczej (D_{50}) gruntów niespoistych bezpośrednio na podstawie wyników badań DMT. Ponadto obliczone na podstawie proponowanej współzależności wartości D_{50} zostały zweryfikowane przy użyciu wyników badań laboratoryjnych gruntów z innych obiektów nieuwzględnionych w analizie podczas opracowywania proponowanej współzależności empirycznej.

Słowa kluczowe: badanie in situ, grunt mineralny, uziarnienie piasku